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RESEARCH ARTICLE

Cooperative operation of the Grand Ethiopian Renaissance Dam reduces Nile riverine floods

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Abstract

The construction of the Grand Ethiopian Renaissance Dam (GERD) on the Nile River has triggered much debate between Ethiopia, Sudan, and Egypt on the dam's effects. Once completed, the GERD will be Africa's largest hydropower plant. This study analyzes the implications of cooperative long-term operation of the GERD for Nile riverine flooding downstream of the dam. A daily river system model of the Eastern Nile is developed and used to examine how cooperative long-term operation of the GERD would affect the occurrence of three flood alarm levels (*alert*, *critical*, and *flooding*) in Sudan downstream of the dam. A reconnaissance-level flood inundation model is developed for the Nile within Khartoum State (Sudan's capital) to assess the GERD's impacts on the flood extent in the state based on simulated flows from the river system model. Assuming the GERD is operated to achieve a 90% power reliability and active upstream-downstream data sharing between Ethiopia and Sudan on the dam's daily outflows, results show that the GERD would reduce the occurrence of the three alarm levels. Based on 34 simulated river flow sequences, the proportion of years with at least one *flooding* alarm day at Khartoum Gage declined from 37% without the GERD to 11% with the GERD. Seasonal coordination and planning between Ethiopia and Sudan are necessary to mitigate the remaining riverine flood hazard. Although cooperative long-term operation of the GERD could play a positive role in reducing the riverine flood hazard in Sudan, the associated river flow alterations would adversely impact recession agriculture and the environment.

KEYWORDS

Coordination, GIS Flood Tool, hydropower, large dams, Nile Basin, RiverWare

1 | INTRODUCTION

Floods provide social, economic, and environmental benefits (Cuny, 1991); however, if not managed appropriately, they can damage properties and result in losses in lives and livelihoods. Riverine floods occur due to excessive rainfall and/or snowmelt, causing overflow outside the river channel to the floodplains. The Nile, one of the longest rivers globally, has a basin covering around 10% of Africa's land surface.

The Blue Nile (see Figure 1a) is a major tributary of the Nile, originates in the Ethiopian highlands, and contributes around 57% of the Nile flow at the Sudanese–Egyptian border (Nile Basin Initiative, 2012). The Blue Nile is known for its high seasonality (see Figure S1 in the supplementary material). On average, around 80% of the annual flow of the Blue Nile occurs in four months (Basheer & Elagib, 2019).

The Nile River in Ethiopia holds a significant hydropower potential (Nile Basin Initiative, 2012). In 2011, Ethiopia started constructing

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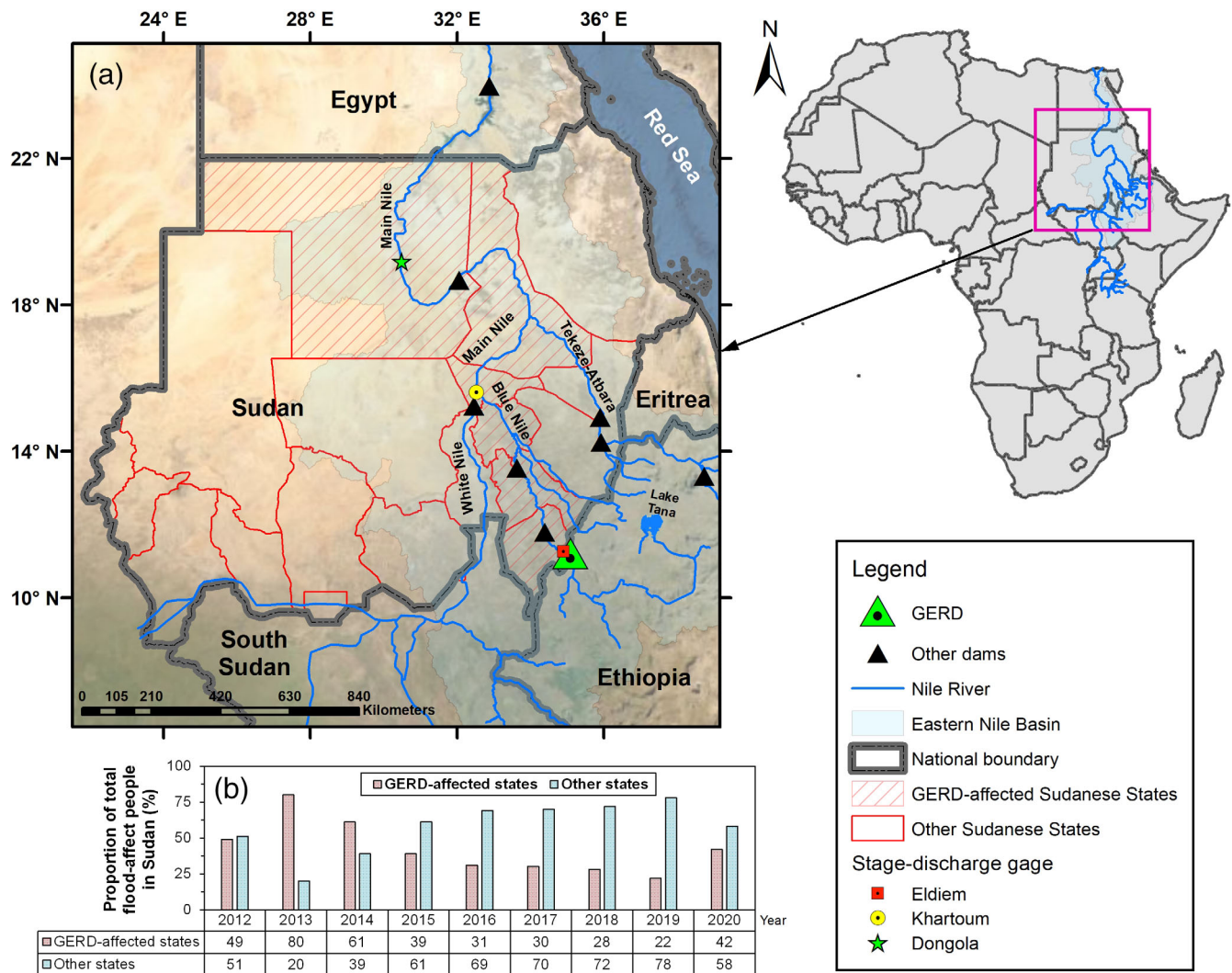


FIGURE 1 Main features of the study region: (a) dams and rivers in the Eastern Nile Basin; (b) flood-affected people in Sudan from 2012 to 2020. Note: GERD, Grand Ethiopian Renaissance Dam. Panel b is based on data from the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

the Grand Ethiopian Renaissance Dam (GERD)—the largest hydropower plant in Africa and among the largest worldwide (Mulligan, van Soesbergen, & Sáenz, 2020)—on the Blue Nile River for hydropower production, and the initial filling of the dam's reservoir started in July 2020. The GERD is located around 15 km upstream of the Ethiopia-Sudan border and is planned to have an installed power capacity of 5,150 MW and a maximum reservoir storage capacity of 74,000 Mm³. The dam's storage capacity is around 1.5 times the average annual river flow at the dam location. Because the purpose of the GERD is electricity generation, its high storage capacity is expected to regulate the Blue Nile flow and potentially benefit Sudan in terms of irrigation water reliability and hydropower generation (Wheeler et al., 2016). However, the dam is expected to pose adverse environmental impacts and a loss of recession agriculture in Sudan (Alrajoula, Al Zayed, Elagib, & Hamdi, 2016; Elagib & Basheer, 2021). Moreover, the operation of the GERD would reduce Egypt's hydropower generation (Wheeler et al., 2016). Depending on how the GERD is operated

during multi-year droughts, the dam could result in irrigation water deficits in Egypt (Wheeler, Jeuland, Hall, Zagana, & Whittington, 2020). Negotiations between Ethiopia, Sudan, and Egypt on the initial filling and long-term operation of the dam are ongoing since 2011. Recently, the United States Government, the World Bank, and the African Union hosted and convened several rounds of negotiations between the three countries, but no agreement has been reached as of April 20, 2021.

Several previous studies assessed the impacts of the GERD on Ethiopia, Sudan, and Egypt as a result of changes to water availability for irrigation and hydropower generation (Arjoon, Mohamed, Goor, & Tilmant, 2014; Basheer et al., 2020, 2018; Digna et al., 2018a; Digna et al., 2018b; Eldardiry & Hossain, 2020; Elsayed, Djordjevic, Savic, Tsoukalas, & Makropoulos, 2020; Kahsay et al., 2019; King & Block, 2014; Liersch, Koch, & Hattermann, 2017; Mulat & Moges, 2014; Siddig, Basheer, & Luckmann, 2021; Wheeler et al., 2016, 2020; Wheeler et al., 2018a; Zhang, Block, Hammond, & King, 2015; Zhang,

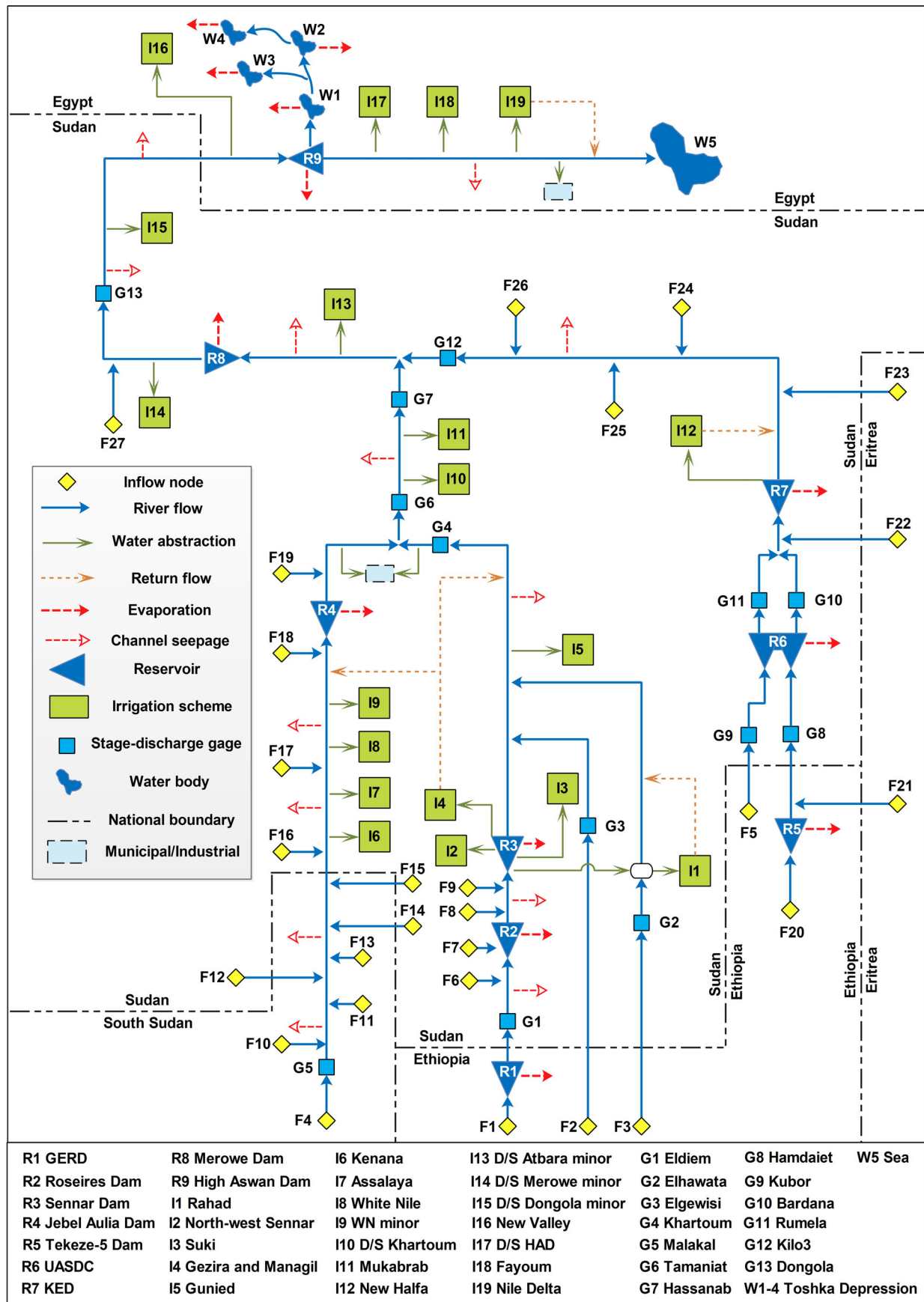


FIGURE 2 Schematic of the daily river system model of the Eastern Nile Basin developed in this study. Note: GERD, Grand Ethiopian Renaissance Dam; UASDC, Upper Atbara and Setit Dam Complex; KED, Khashm Elgirba Dam; D/S, downstream; HAD, High Aswan Dam [Color figure can be viewed at wileyonlinelibrary.com]

Erkyihum, & Block, 2016). However, no study in the published literature analyzed the long-term impacts of the GERD on the riverine flood hazard along the Blue Nile and the Main Nile. The presence of the High Aswan Dam—a large multi-year storage dam—in Egypt near the Sudanese-Egyptian border means the GERD would not benefit Egypt in terms of riverine flood control, as the High Aswan Dam controls riverine floods in the country. The GERD is expected to change the riverine flood hazard in six of Sudan's 18 states (Figure 1a). Around 22–80% of the total flood-affected people in Sudan (from both flash and riverine floods) during the period 2012–2020 were located in these six states (Figure 1b; OCHA (2021)).

This study assesses the impacts of cooperative long-term operation of the GERD on the riverine flood hazard in Sudan and recommends measures for mitigating the associated challenges. The author developed and used a daily river system model of the Eastern Nile Basin and a reconnaissance-level riverine flood inundation model of Khartoum State (Sudan's capital) to examine the impacts of cooperative long-term operation of the GERD on the flood hazard of the Nile. The river system model was calibrated and validated over the period from 1983 to 2017 and includes a detailed representation of the daily operations of the major water-related infrastructures in the river system. The flood inundation model of Khartoum State was based on satellite topographic data and was driven by simulated flows from the daily river system model.

2 | METHODOLOGY

2.1 | Eastern Nile River system model

In this study, a daily river system model was developed for the Eastern Nile Basin downstream of the GERD. A river system model is a numerical network representation of the water supplies and demands, infrastructures, and operating rules of a river. Figure 2 depicts a schematic of the model. The model includes 27 inflow nodes, 9 storage dams, 21 water withdrawal nodes, 13 stage-discharge gages, reservoir evaporation, and channel seepage from 13 river reaches. Table S1 in the supplementary material reports the main characteristics of the nine storage dams included in the model. The stage-discharge gages are populated with rating curves to translate river flows to river water levels. A rating curve is a relationship between the river discharge and the river water level of a specific river cross-section. The generated water levels were then utilized to calculate the number of days within each of three flood alarm levels used in Sudan by the Ministry of Irrigation and Water Resources: *alert*, *critical*, and *flooding*. These alarm levels are based on thresholds of river water levels. Table S2 in the supplementary material reports the definitions of the three alarm levels for Eldiem (G1), Khartoum (G4), and Dongola (G13) stage-discharge gages. Figure S2 depicts an illustrative example for how the simulated daily flows and the rating curves were used to calculate the number of *alert*, *critical*, and *flooding* days. The water year (June 1 to May 31) was used in the model instead of the calendar year (January 1 to December 31) because the operating rules of the

seasonal storage dams in the river system are based on the water year.

The model is driven by hydrological inflows at nodes F 1–27 and the system operating rules. The observed flow records of the Nile at Eldiem (G1), Elgewisi (G3), Elhawata (G2), Malakal (G5), and Kubur (G9) gages were used as inflows for the nodes F1, F2, F3, F4, and F5, respectively. Data for the rest of the inflow nodes were obtained from hydrological models previously developed by Basheer et al. (2018), Basheer and Elagib (2018), and Basheer, Sulieman, and Ribbe (2021). Average monthly evaporation coefficients were used to simulate evaporation from reservoirs. Channel seepage percentages and lag times were populated for the river reaches. Constant percentages were used to estimate the return flows of the Rahad (I1), the Gezira and Managil (I4), and the New Halfa (I12) irrigation schemes (5, 7, and 4%, respectively).

The model was created using RiverWare, a generalized river and reservoir simulation software developed by the University of Colorado Boulder (Zagona, Fulp, Shane, Magee, & Goranflo, 2001). RiverWare can simulate several river system processes using a variety of methods and time steps. RiverWare enables the user to add the system operating rules using logical statements in the RiverWare policy language. This river system simulation software has been termed a “hydro-policy” tool by Wheeler, Robinson, and Bark (2018b) due to its flexibility in modeling water management policies.

2.2 | Calibration and validation of the river system model

The model was calibrated over the period 1983 to 2000 and validated from 2001 to 2017. Channel seepage, return flows, and lag times were used as calibration parameters. The available observed data on the outflow from the Roseires (R2), the Sennar (R3), and the Khashm Elgirba (R7) dams, the reservoir water levels of the Jebel Aulia Dam (R4) and the High Aswan Dam (R9), and the flow at Khartoum (G4), Tamaniat (G6), Hassanab (G7), and Dongola (G13) gages were used as benchmarks to calibrate and validate the model. The performance of the model was assessed and ranked following the recommendations of Stern, Flint, Minear, Flint, and Wright (2016) based on the coefficient of determination (R^2), the Nash-Sutcliffe coefficient of efficiency (NSE), and the Mean Error Percentage (MEP). Table S3 in the supplementary material reports the performance metrics and the rankings of the model at nine locations. The model showed predominantly excellent performances in the calibration and validation periods. The simulated and observed river flows and reservoir levels are presented in Figures S3 to S11 in the supplementary material.

2.3 | Flood inundation model

The GIS Flood Tool (GFT; Verdin et al. (2016)) was used to develop a reconnaissance-level flood inundation model for the Nile within Khartoum State, Sudan. GFT was developed by the U.S. Geological Survey

supported by the U.S. Agency for International Development's Office of U.S. Foreign Disaster Assistance. GFT uses Digital Elevation Model (DEM) data to map the flood inundation extent and depth for user-specified streamflow values. Flood mapping in GFT is based on the Manning Equation for steady flow in open channels (Manning, 1891). In GFT, the river stream is divided into segments, and a river cross-section is generated for each segment to construct a depth-discharge curve based on the Manning Equation. GFT can provide useful information on flood inundation in data-scarce regions like the Nile Basin. Although GFT uses simplified approaches, its validation by Verdin et al. (2016) showed agreement with one-dimensional hydraulic models at 11 sites in the United States, one site on the Okavango River in Namibia, and two sites on the Blue Nile River in Sudan.

In this study, the Shuttle Radar Topography Mission (SRTM) DEM version 3 data, which have a 30-m spatial resolution, were used with GFT to develop a flood inundation model for the Nile within Khartoum State. Khartoum State is where the Blue Nile and the White Nile meet to form the Main Nile (see Figure 1). Khartoum is the most populated state in Sudan, with around 7.4 million inhabitants, representing around 16% of Sudan's total population (Population data, 2020). In developing the flood inundation model, the Blue Nile and the Main Nile were divided into 20-km segments to reflect topographic variations while avoiding discontinuities in the simulated flood extent and reducing computational costs. A river and floodplain cross-section was generated for each segment with a width of around 24 km. Figure S12 in the supplementary material shows the river segments and the cross-sections generated for the Blue Nile and the Main Nile. A Manning coefficient of roughness of 0.045 was assumed for all river cross-sections based on general estimates by Chow (1959). The flood inundation model was driven by daily simulated streamflow values generated using the river system model described in Section 2.1.

2.4 | Data sources

The observed river flows and reservoir water levels, water withdrawal targets, and dams' characteristics were obtained from Copernicus Global Land Service (2021), Omar (2013), Abdelkader et al. (2018), Basheer et al. (2021), Wheeler et al. (2016), and the Ministry of Irrigation and Water Resources of Sudan. The inflows of nodes F6-27 (see Figure 2) were obtained from Basheer et al. (2018), Basheer and Elagib (2018), and Basheer et al. (2021). The geometry and spill data of the Toshka lakes (or Toshka Depression) were obtained from Fassieh and Zaki (2014).

2.5 | Simulation assumptions and scenarios

In this study, it was assumed that the long-term operation of the GERD starts with reservoir storage of 49,300 Mm³, following the outcomes of recent negotiations between Ethiopia, Sudan, and Egypt (Amde, 2020; Edrees, 2020). An energy-oriented operation was

assumed for the GERD by targeting a power production of 1,600 MW (38.4 GWh/day) to achieve a 90% power reliability, as revealed by Wheeler et al. (2018a). A higher priority was given to keeping the reservoir water level between the minimum operating and full supply levels. It was assumed that Sudan's Roseires, Sennar, and Merowe dams (see Figure 2) are operated at their full supply levels and are allowed to drop only to meet the water or energy demands. Wheeler et al. (2016) and Basheer et al. (2018) found that this configuration eliminates the water supply shortages in Sudan. All other dams in Sudan were operated using their historical operating rules in both the baseline and with the GERD. Table S4 in the supplementary material summarizes the assumed operating rules of the GERD, the Roseires Dam, the Sennar Dam, and the Merowe Dam during the long-term operation of the GERD.

Cooperation on transboundary rivers can occur in various forms ranging from unilateral action to joint action (Sadoff & Grey, 2005). In this study, cooperation between Ethiopia and Sudan in the form of active upstream-downstream data sharing on the GERD's daily outflows (i.e., instant downstream knowledge at each simulated time step) was assumed in modeling the operation of the Roseires, the Sennar, and the Merowe dams.

To examine the impact of the GERD on the riverine flood hazard in Sudan, two scenarios were simulated: (a) a baseline scenario without the GERD in which the river system is operated following the historical rules, and (b) a scenario in which cooperative long-term operation of the GERD is introduced, and the operation of the Roseires, the Sennar, and the Merowe dams are modified as explained earlier. The two scenarios were examined across 34 river flow sequences (or traces) generated using the index-sequential method (Kendall & Dracup, 1991; Ouarda, Labadie, & Fontane, 1997). Each of the river flow sequences is 34-year long. The index-sequential method uses the historical record of river flows to generate river flow sequences assuming that every year in the record is a possible starting point. This method was used because it is non-parametric and preserves the serial and spatial correlations in the historical flow data. However, it does not capture non-stationarity in the hydrologic system (e.g., climate change) and river flow patterns outside the historical record. The 34 hydrologic sequences were based on the daily flow data of the 27 inflow nodes of the river system model (Figure 2) for June 1983 to May 2017.

3 | RESULTS

Results reveal that cooperative operation of the GERD to achieve a 90% power reliability (see Section 2.5 for details) would change the pattern of river flows and water levels of the Blue Nile and the Main Nile in Sudan. Figure 3 shows box plots of the annual number of days in each of the three alarm categories used in Sudan (i.e., *alert*, *critical*, and *flooding*; see Table S2 in the supplementary material for their definitions) with and without the GERD. The figure shows the annual number of alarm days at three locations in Sudan: Eldiem, Khartoum, and Dongola gages. As Figures 1 and 2 show, Eldiem Gage is located

on the Blue Nile near the Ethiopian-Sudanese border, Khartoum Gage is located on the Blue Nile close to the confluence of the White Nile and the Blue Nile, and Dongola Gage is located on the Main Nile upstream of the Sudanese-Egyptian border.

Overall, the results show that the GERD would reduce the annual number of days in each of the three alarm categories. This reduction is due to the GERD's river flow regulation effect resulting from targeting a 90% power reliability. The median annual number of *alert* days declined from 57 to 0, from 22 to 0, and from 32 to 2 at Eldiem, Khartoum, and Dongola gages, respectively, with the GERD compared to the baseline scenario. The maximum annual number of *alert* days dropped by 38, 16, and 21 at Eldiem, Khartoum, and Dongola gages, respectively. A zero median annual number of *critical* and *flooding* alarm days were recorded at all locations in the scenario that includes the GERD. At Khartoum Gage, the maximum annual number of *flooding* alarm days declined from 10 in the baseline to 2 with the GERD. The percentage of years with at least one *flooding* alarm day at Khartoum Gage declined from 37% in the baseline to 11% with the GERD. No *flooding* alarm days were recorded at Dongola Gage in both the baseline and the GERD scenario. This occurred because Dongola Gage is located downstream of the largest storage reservoir in Sudan

(i.e., Merowe), which can eliminate the *flooding* days at Dongola in the baseline.

It was found that cooperative operation of the GERD to achieve a 90% power reliability would reduce the riverine flood hazard in Sudan on the Blue Nile and the Main Nile. Nevertheless, the results suggest that the occurrence of floods remains possible, especially at Khartoum Gage, as indicated by a maximum of two *flooding* alarm days and 11% of the simulated years with at least one *flooding* alarm day (see Figure 3h). Figure 4 shows the daily simulated reservoir storage and outflow of the GERD for one of the 34 examined river flow sequences. During successions of high inflow years that coincide with high GERD water levels, the GERD would reach its full supply level and pass higher water volumes than the volumes required for generating the assumed 1,600 MW power target (or 38.4 GWh/day).

Figure 5 compares the extent of flood inundation in Khartoum State with and without the GERD for a hydrological year similar to 1988, in which severe floods occurred in Khartoum (Sutcliffe, Dugdale, & Milford, 1989). The figure compares the extent of flood inundation in two situations: (a) the GERD reservoir starts the hydrologic year low at 595 meters above sea level (masl), equivalent to 18500 Mm³ storage, and (b) the GERD reservoir starts the

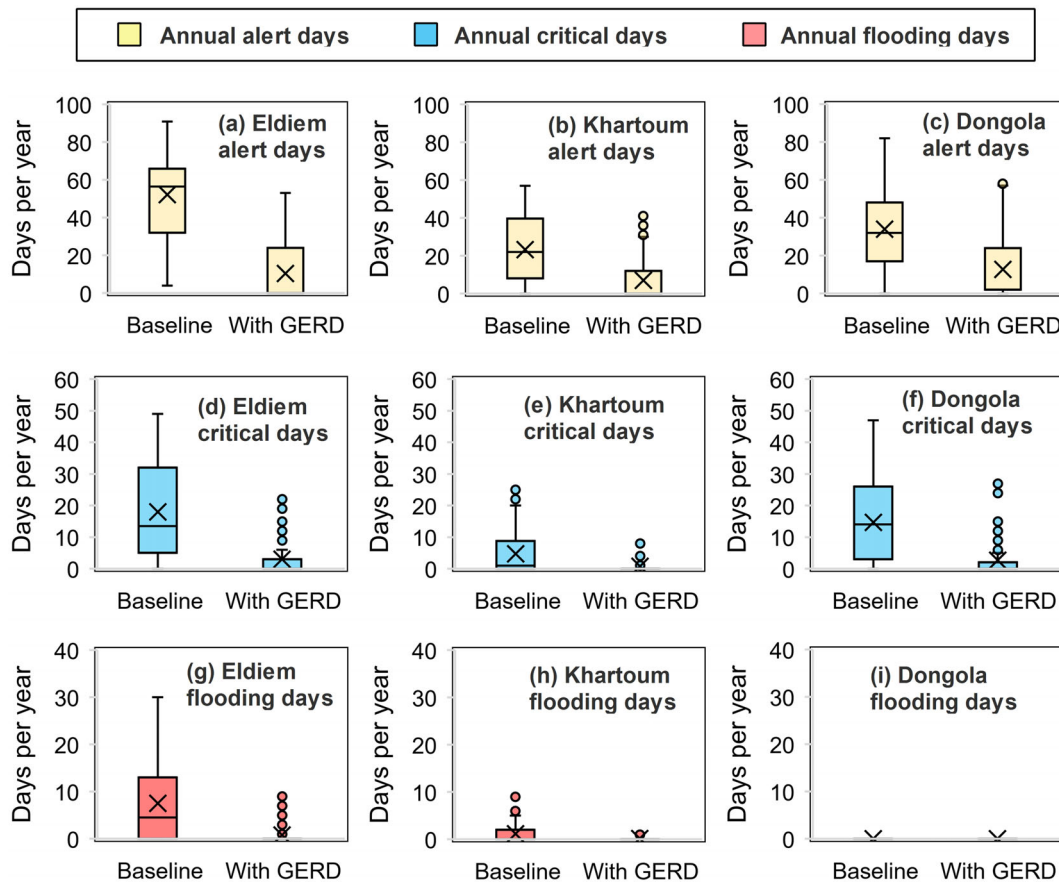
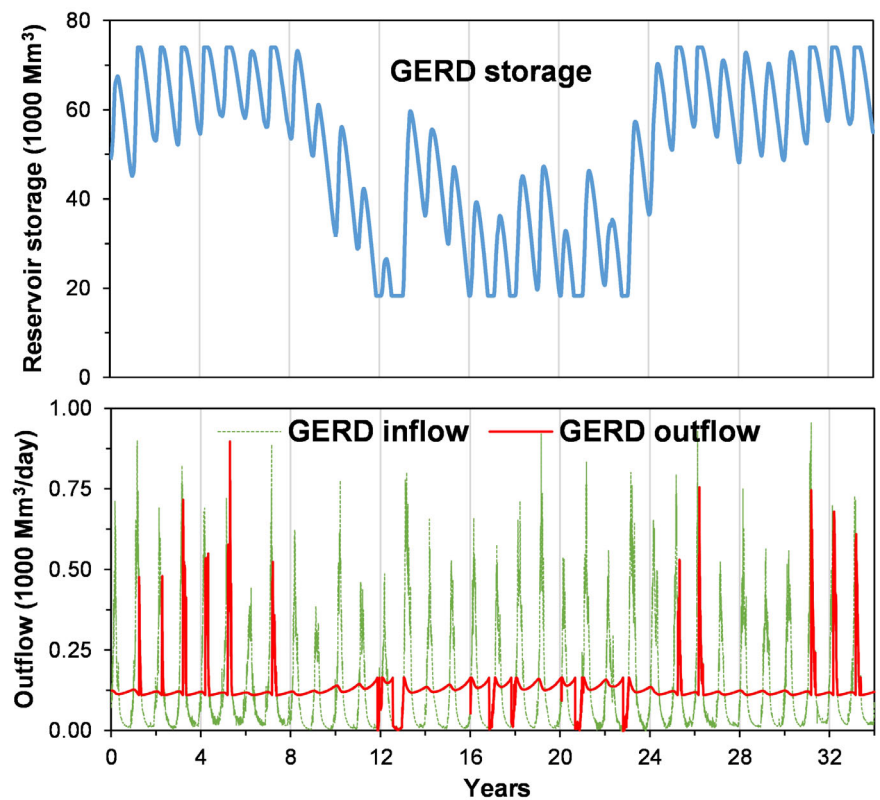


FIGURE 3 Box plots demonstrating the impacts of GERD's long-term operation on the annual occurrence of three flood alarm levels (*alert*, *critical*, and *flooding*) at three locations in Sudan (Eldiem, Khartoum, and Dongola gages). The ends of the boxes represent the upper and lower quartiles, the horizontal lines inside the boxes mark the medians, the crosses mark the mean, the circles show the outlier, and the whiskers extend to the maximum and minimum values. Note: GERD, Grand Ethiopian Renaissance Dam [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 4 Daily reservoir storage, inflow, and outflow of the Grand Ethiopian Renaissance Dam (GERD) based on one of the 34 examined river flow sequences [Color figure can be viewed at wileyonlinelibrary.com]



hydrologic year relatively high at 625 masl, equivalent to 49,300 Mm³ storage. Note that the flood extent presented in Figure 5 is for Khartoum State only and not for all the river reaches impacted by the GERD. Figure 5a shows a reduction in the inundated area in Khartoum State by around 68% when the GERD reservoir starts the simulated year at 595 masl with sufficient free storage to regulate the Blue Nile flow. The reduction in the inundated area decreases to around 10% when the GERD reservoir starts the simulated year at 625 masl (Figure 5b).

4 | DISCUSSION

The results show that high outflows from the GERD could occur during the dam's long-term operation, as depicted in Figure 4. Such conditions would happen after several years of regulated river flows during which the populations that reside along the Blue Nile and the Main Nile would have adapted to a new regular river flow regime and settled in flood-prone areas. This human behavioral change could result in an increased flood vulnerability and values (e.g., buildings) at risk (Kron, 2005). Mitigating the impacts of high outflows from the GERD requires seasonal coordination and planning between Ethiopia and Sudan on dam operation in addition to active daily data sharing. Seasonal coordination and planning and active data sharing would enable Sudan to gradually drawdown the Roseires, the Sennar, and the Merowe reservoirs (see Figure 2) to partly absorb the impact of high GERD outflows. Furthermore, awareness of the populations living along the Blue Nile and the Main Nile in Sudan should be raised

against complacency, given the anticipated sporadic occurrence of riverine floods. In this study, the GERD was assumed to target 1,600 MW of power generation to achieve a 90% power generation reliability (Wheeler et al., 2018a). Adjusting the assumed operation of the GERD by increasing the power target would reduce intense daily downstream outflows to Sudan and, in turn, the flood hazard, but would cost a decline in the dam's power reliability and/or annual electricity generation, given the high interannual variability (see Figure S1 in the supplementary material) and low predictability of the Blue Nile flow.

The impact of cooperative operation of the GERD to achieve a 90% power reliability on flood occurrence in Khartoum would/should affect the operation of the Jebel Aulia Dam, which is located on the White Nile around 40 km upstream of the confluence of the Blue Nile and the White Nile (see Figure 1). The outlets of the Jebel Aulia Dam are usually closed when the water level at Khartoum Gage exceeds certain thresholds during the flood season of the Blue Nile in July–October (Basheer & Elagib, 2018; Sobeir, 1983) to reduce flooding along the Main Nile and prevent backflow into the Jebel Aulia Reservoir. Flow regulation of the Blue Nile at Khartoum would provide flexibility to the operation of the Jebel Aulia Dam.

Although floods are often associated with destruction and damage, they provide environmental and economic benefits. Generally, river flow regulation results in a loss of natural floodplains and negatively affects the flora and fauna that rely on the floodplains (Brismar, 2004; Cuny, 1991). Recession agriculture is widely practiced along the Blue Nile and the Main Nile in Sudan. A regular flow of the Blue Nile would result in a loss of recession agriculture and affect

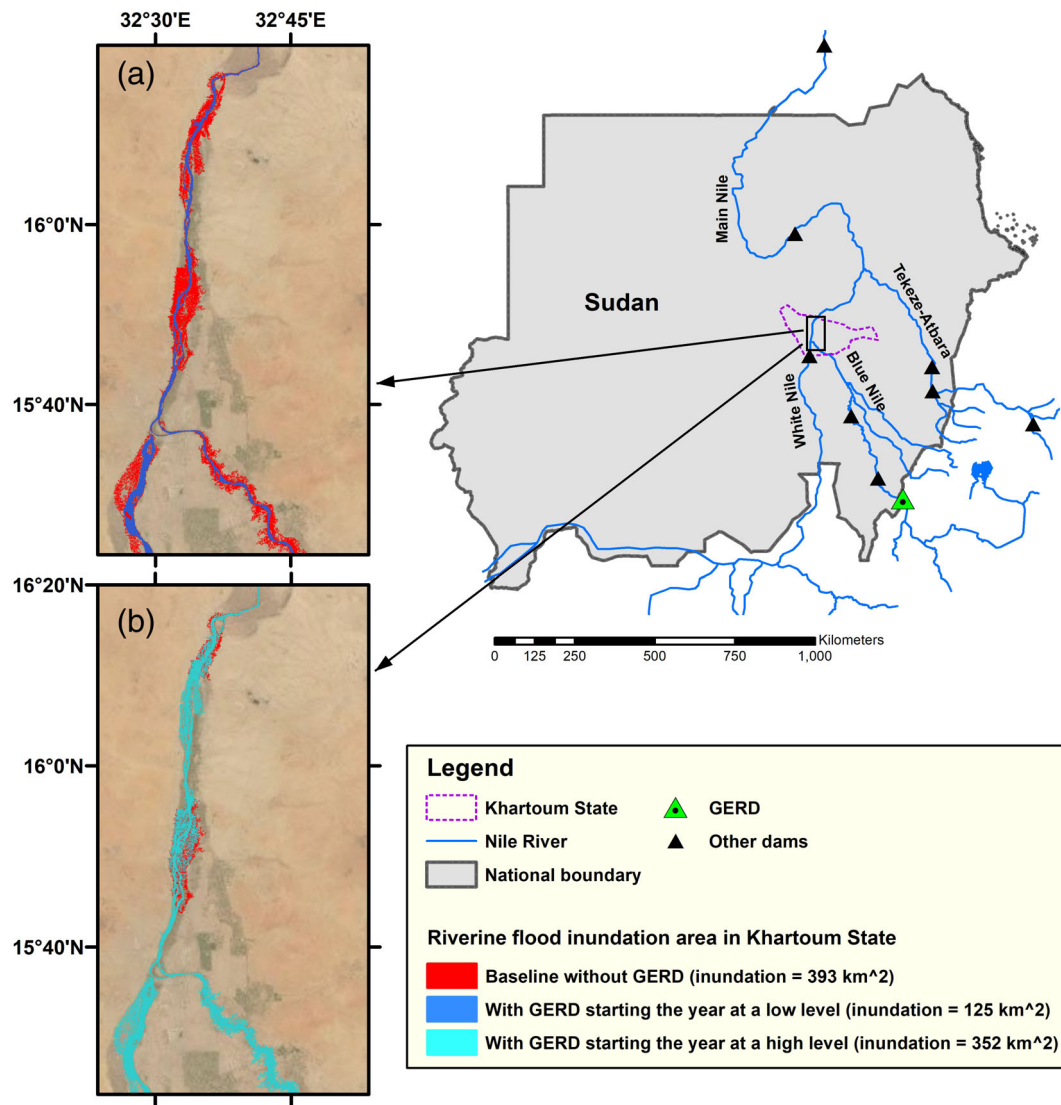


FIGURE 5 Simulated riverine flood inundation in Khartoum State, Sudan, in a hydrological year similar to 1988: (a) a river flow sequence in which the reservoir of the GERD starts the simulated hydrological year at 595 masl; (b) a river flow sequence in which the reservoir of the GERD starts the simulated hydrological year at 625 masl. The flood extent presented in this figure is for Khartoum State only and not all the river reaches impacted by the GERD. Note: GERD, Grand Ethiopian Renaissance Dam [Color figure can be viewed at wileyonlinelibrary.com]

the livelihoods of thousands of farmers in Sudan (Mohammed, 2015). Moreover, the hydrological alterations associated with the operation of the GERD would affect the water temperature, salinity, suspended nutrients, and oxygen content downstream of the dam and adversely impact aquatic life and biodiversity (Elagib & Basheer, 2021).

5 | CONCLUSIONS

This study showed that cooperative (i.e., active daily data sharing) energy-oriented long-term operation of the GERD would reduce Nile riverine floods in Sudan. Mitigating the remaining riverine flood hazard requires seasonal coordination and planning in addition to active daily upstream-downstream data sharing between Ethiopia and Sudan. Climate change is expected to alter the amount and variability

of the Nile streamflow (Siam & Eltahir, 2017), and cooperative operation of the GERD could contribute to reducing the riverine flood hazard of these anticipated changes.

Although cooperative energy-oriented operation of the GERD would reduce the riverine flood hazard in six states in Sudan, a large proportion of flood-affected people in the country would not benefit from reduced Nile riverine floods. Flash floods are the more common and frequent cause of flood-related losses and disruptions in the six GERD-affected states in Sudan (Mahmood, Elagib, Horn, & Saad, 2017; Mahmoud, Elagib, Gaese, & Heinrich, 2014; Zerboni et al., 2020) and the rest of the country. In addition to the positive role that the GERD could play in reducing the riverine flood hazard of the Nile, mitigating the risk of floods (including flash floods) in Sudan requires adaptive flood management measures, good governance, sound urban planning, well-designed drainage infrastructure, adequate

health services, and public awareness of flood risks (Elagib, Gayoum Saad, Basheer, Rahma, & Gore, 2021; Horn & Elagib, 2018; Mahmood et al., 2017; Mahmoud et al., 2014).

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CONFLICT OF INTEREST

The author reported no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data and model that support this study's findings are not publicly available due to third-party restrictions. The Digital Elevation Model (DEM) data used in developing the flood inundation model are freely accessible at: <https://earthexplorer.usgs.gov/>.

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SUPPORTING INFORMATION

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